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A goal programming model for the optimal mix and location of renewable energy plants in the north of Spain

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ABSTRACT

The capacity expansion planning problem of the renewable energy industry involves decisions regarding the optimal mix of different plant types, locations where each plant should be built, and capacity expansion decisions over the planning horizon for each plant. The aim of this paper is to develop a goal programming model, based on a multi-source multi-sink network, in order to locate five renewable energy plants for electric generation in five places located in the autonomous region of Cantabria, in the north of Spain. As different types of plants can be placed in each location, the goal is to locate one plant in each place, maximizing the number of plants that are matched with comparable locations, in a way that the total deviations from goals are minimized.

Contents

1. Introduction

Mitigation of climate change, in order to reach the targets set by the Kyoto Protocol, requires significant reductions of Greenhouse Gas emissions and, consequently, the adequate policy formulation for fossil fuel energy substitution by renewable energy sources. In modern technologically developed societies, where the complexity of the interactions between the economic activities and environmental systems are recognized, strategic decisions must be made under an increasingly complex and unstable environment, characterized by a fast pace of technological evolution, changes in market structures, and new societal concerns [1]. These problems demand the use of analytical tools that describe and evaluate the problem in its social, environmental, economic and technological dimension.

The capacity expansion planning problem of the renewable energy industry is not only concerned with the selection of the best renewable energy project among different alternatives, but also with developing expansion plans for the generation, transmission and distribution systems. Such plans involve decisions regarding the optimal mix of different plant types, locations where each plant should be built, and capacity expansion decisions over the planning horizon for each plant. A multitude of technical, financial, environmental, legal, social and political objectives and/or constraints, some of which are not even quantifiable, some of which are conflicting, participate in the decision process, rendering capacity expansion planning in the power field a very complex issue [2].

In this paper a Goal Programming model, based on a multi-source multi-sink network, is presented. The paper is organized as follows. In the next section the Goal Programming methodology is shown. Next, the model is applied to locate five renewable energy plants for electric generation in five places located in the autonomous region of Cantabria, in the north of Spain. Finally, a concluding section with the main results of the paper is presented.

2. The goal programming model

Although Goal programming is itself a development of the 1950s, it has only since the mid-1970s that Goal programming

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received truly substantial attention. Much of the reason for such interest results from Goal programming's demonstrated ability to serve as an efficient and effective tool for the modeling, solution, and analysis of mathematical models that involve conflicting goals and objectives [3].

Goal programming can be used to help satisfying decision-makers to attack problems in which a multitude of conflicting goals exist. During recent years, the increasingly complex social, economic, technological and environmental scenario has made multi-criteria analysis a valuable tool in the selection of renewable energy projects. As a result, multi-criteria decision-making methods such as Analytical Hierarchy Process, ELECTRE, PROMETHEE, TOPSIS, VIKOR, have been extensively used in the selection of renewable energy projects in areas such as wind-farm projects, geothermal projects, hydro-site selection, etc. [4–14].

Whereas these methods have been widely used in the renewable energy industry, the use of the Goal Programming methodology in the selection of renewable energy plants, locations, or capacity expansion decisions has been limited to a few works. Koroneos et al. [15] applied a multi-objective model on the island of Lesvos, Greece, where various renewable energy sources can be exploited with the existing conventional systems to satisfy the needs of the island's economy. Daim et al. [16] developed a fuzzy goal programming model for the state of Oregon to create a renewable energy portfolio with the objective of responding to a 25 percent of the electricity demand by renewable resources in 2025. Jinturkar and Deshmukh [17] developed a fuzzy mixed integer goal programming model for rural cooking and heating energy planning in Central India.

In linear programming, only one objective is permitted, thus, even though multiple goals may confront the decision-maker, all progress towards these goals must be measured on a common scale, often profit or cost. The largest drawback of linear programming is that it requires unidimensionality in the objective function; that is, all goals must be expressed in common units and combined to give an overall single measure of effectiveness. The requirements are that the decision-maker must be able to establish and prioritize the goals and to express the relationships between the decision variables and goals with linear functions. Once the decision-maker has provided an ordinal ranking of the goals, the goal programming model minimizes the deviations from the goals subject to the constraints that have been set.

The general form of a Goal Programming problem may be expressed as

$$\text{Minimize} \quad \sum_i (d_i^+ + d_i^-)$$

$$s.t.$$

$$\sum_{j=1}^{n} (a_{ij} x_j) d_i^+ + d_i^- = b_i$$

$$x_j + d_i^-, d_i^+ \geq 0 \tag{1}$$

where d_i^- is the amount by which goal i is underachieved, d_i^+ is the amount by which goal i is overachieved, $x_j (j=1,2,\ldots,n)$ are the variables in the goal equations, $b_i (i=1,2,\ldots,m)$ are the targets or goals, and a_{ij} are the coefficients of the variables.

3. Application

The aim of this section is to develop a goal programming model in order to locate five renewable energy plants for electric generation in five places located in the autonomous region of Cantabria, in the north of Spain. Seven plants (alternatives) are candidate to be placed in these seven locations: La Braguía, La Vega, Estacas, Lunada, Potes, Reinosa, and Santander. The attributes considered in order to evaluate the designed systems are: Power (*Gw*), Investment (*I*), Tons of emissions of CO_2 avoided per year (TCO_2/y), Operation and Maintenance costs (*OM*), Jobs (*J*), Distance between plants (*D*), and Social acceptance (*S*). Table 1 shows the data for the first five criteria [18], Table 2 shows the distance between locations and Table 3 the social acceptance expressing the overview of opinions related to the energy systems by the local population regarding the hypothesized realization of the renewable energy projects. Let us consider for analytical purposes, that the index social acceptability has been expressed by the local population in a scale of 1 (low acceptance) to 10 (high acceptance).

Table 4 shows the comparability between plants and locations. As different types of plants can be placed in each location, the goal is to locate one plant in each place in a way that the total deviations from goals are minimized. Let us consider that the autonomous government establishes the following goals: the power generated, emissions avoided and jobs created must be higher than 110×10^6 Gw, 18×10^6 t, and 70 jobs; with regard to investment and operation and maintenance costs, these figures must be limited to 100×10^6 € and 350,000 €/year respectively. The distance between plants must be maximized to 2910 Km and the social acceptance must be as close as possible to the highest level (50).

Fig. 1 shows the appropriate network, where each plant is a source node and each location is a sink node. By adding a super source node connected to each source and a supper sink node connected to each sink, the multi-source multi-sink problem is transformed into a maximum flow problem that maximizes the number of plants that are matched with comparable locations.

Table 2
Distances between locations (Km).

	La Braguía	*La Vega*	*Estacas*	*Lunada*	*Potes*	*Reinosa*	*Santander*
La Braguía	–	6.5	15	39	126	61	53
La Vega		–	8	32	121	54	65
Estacas			–	24	128	62	72
Lunada				–	143	78	56
Potes					–	130	107
Reinosa						–	75
Santander							–

Table 1
Alternatives for electric generation [18].

Alternative	*Gw*	*I*	TCO_2/y	*J*	*OM*
Wind power ($10 \leq P \leq 50$ MW)	60,959,000	23,425,000	9,649,680	15	37,750
Hydroelectric ($P \leq 10$ MW)	3,940,100	7,500,000	472,812	8	7250
Hydroelectric ($10 \leq P \leq 25$ MW)	962,000	14,000,000	255,490	8	14,000
Hydroelectric ($25 \leq P \leq 50$P MW)	412,000	21,035,000	255,490	12	21,000
Solar ($P \geq 10$ MW)	306,031	5,320,000	482,856	10	1792
Biomass ($P \leq 5$ MW)	13,612,500	9,015,000	2,524,643	15	27,100
Biomass ($P \geq 50$ MW)	37,770,000	47,958,400	4,839,548	20	75,000

There is an arc joining the super source to each plant, and an arc joining each pair of compatible matches, and an arc joining each place to the super sink. Because arcs do not exist between noncomparable mates, a flow of k units from the super source to the super sink represents an assignment of plants to places in which k compatible couples are created. Because the arc joining each place to the super sink has a capacity of 1, conservation of flow ensures that each place will be matched with at most one plant. Similarly, because each arc from the source to a plant has a capacity 1, each plant can be pared with at most one place. The formulation for this goal programming model can be expressed as

$$\text{Minimize} \quad \sum_i (d_1^- + d_2^+ + d_3^- + d_4^- + d_5^+ + d_6^- + d_7^-) \tag{2}$$

s.t.

$$60{,}959{,}000F_{1,8} + \ldots + 37{,}770{,}000F_{7,14} + d_1^- - d_1^+ = 110{*}10^6 \tag{3}$$

$$23{,}425{,}000F_{1,8} + \ldots + 47{,}958{,}000F_{7,14} + d_2^- - d_2^+ = 100{*}10^6 \tag{4}$$

$$9{,}649{,}680F_{1,8} + \ldots + 4{,}839{,}548F_{7,14} + d_3^- - d_3^+ = 18{*}10^6 \tag{5}$$

$$15F_{1,8} + \ldots + 20F_{7,14} + d_4^- - d_4^+ = 70 \tag{6}$$

$$37{,}750F_{1,8} + \ldots + 75{,}000F_{7,14} + d_5^- - d_5^+ = 350{,}000 \tag{7}$$

$$6{,}5F_{8,Si} + \ldots + 74F_{14,Si} + d_6^- - d_6^+ = 2910 \tag{8}$$

$$7F_{1,8} + \ldots + 9F_{7,14} + d_7^- - d_7^+ = 50 \tag{9}$$

$$F_{So,Si} - F_{So,1} - F_{So,2} - F_{So,3} - F_{So,4} - F_{So,5} - F_{So,6} - F_{So,7} = 0 \tag{10}$$

$$F_{8,Si} + F_{9,Si} + F_{10,Si} + F_{11,Si} + F_{12,Si} + F_{Si,So} = 0 \tag{11}$$

$$F_{1,8} + F_{2,8} + F_{3,8} + F_{4,8} - F_{8,Si} = 0 \tag{12}$$

$$F_{2,9} + F_{4,9} + F_{6,9} - F_{9,Si} = 0 \tag{13}$$

$$F_{1,10} + F_{3,10} + F_{5,10} + F_{6,10} - F_{10,Si} = 0 \tag{14}$$

$$F_{1,11} + F_{3,11} + F_{5,11} + F_{6,11} + F_{7,11} - F_{11,Si} = 0 \tag{15}$$

$$F_{2,12} + F_{5,12} + F_{7,12} - F_{12,Si} = 0 \tag{16}$$

$$F_{So,1} - F_{1,8} - F_{1,10} - F_{1,11} = 0 \tag{17}$$

$$F_{So,2} - F_{2,8} - F_{2,9} - F_{2,12} = 0 \tag{18}$$

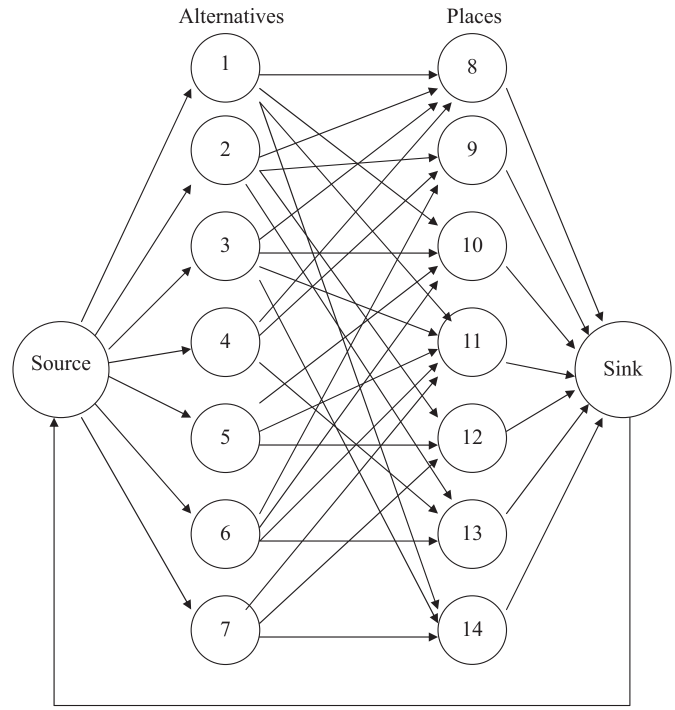

Fig. 1. Multi-source multi-sink network.

Table 5
Places to locate the plants.

Alternative	Location
(1) Wind power ($10 \le P \le 50$ MW)	*Estacas* (10)
(3) Hydroelectric ($10 \le P \le 25$ MW)	*Santander* (14)
(5) Solar ($P \ge 10$ MW)	*Potes* (12)
(6) Biomass ($P \le 5$ MW)	*Reinosa* (13)
(7) Biomass ($P \ge 50$ MW)	*Lunada* (11)

Table 3
Social acceptance (1–10) of each plant in each location.

Alternative	*La Braguía* (8)	*La Vega* (9)	*Estacas* (10)	*Lunada* (11)	*Potes* (12)	*Reinosa* (13)	*Santander* (14)
(1) Wind power ($10 \le P \le 50$ MW)	7		9	7			9
(2) Hydroelectric ($P \le 10$ MW)	5	6			5	7	
(3) Hydroelectric ($10 \le P \le 25$ MW)	6		7	6			7
(4) Hydroelectric ($25 \le P \le 50$P MW)	4	5				6	
(5) Solar ($P \ge 10$ MW)			8	7	9		
(6) Biomass ($P \le 5$ MW)		9	8	8		9	
(7) Biomass ($P \ge 50$ MW)				9	8		9

Table 4
Comparability between plants and locations.

Alternative	*La Braguía* (8)	*La Vega* (9)	*Estacas* (10)	*Lunada* (11)	*Potes* (12)	*Lunada* (13)	*Potes* (14)
(1) Wind power ($10 \le P \le 50$ MW)	*		*	*			*
(2) Hydroelectric ($P \le 10$ MW)	*	*			*	*	
(3) Hydroelectric ($10 \le P \le 25$ MW)	*		*	*			*
(4) Hydroelectric ($25 \le P \le 50$P MW)	*	*				*	
(5) Solar ($P \ge 10$ MW)			*	*	*		
(6) Biomass ($P \le 5$ MW)		*	*	*		*	
(7) Biomass ($P \ge 50$ MW)				*	*		*

Table 6
Deviation from goals.

	Gw	I	TCO_2/y	J	OM	Distance	Social acceptance
Goals	110×10^6	100×10^6	18×10^6	70	350,000	2910	50
Results	113,609,530	99,718,400	17,752,217	68	155,642	2323	43
d_i^+	3,609,530	0	0	0	0	0	0
d_i^-	0	281,600	247,783	2	194,358	587	7

$$F_{So,3}-F_{3,8}-F_{3,10}-F_{3,11}=0 \quad (19)$$

$$F_{So,4}-F_{4,8}-F_{4,9}=0 \quad (20)$$

$$F_{So,5}-F_{5,10}-F_{5,11}-F_{5,12}=0 \quad (21)$$

$$F_{So,6}-F_{6,9}-F_{6,10}-F_{6,11}=0 \quad (22)$$

$$F_{So,7}-F_{7,11}-F_{7,12}=0 \quad (23)$$

$$F_{8,Si}=F_{9,Si}=F_{10,Si}=F_{11,Si}=F_{12,Si}=1 \quad (24)$$

$$F_{8,Si}+F_{9,Si}+F_{10,Si}+F_{11,Si}+F_{12,Si}+F_{13,Si}+F_{14,Si}=5 \quad (25)$$

$$F_{i,j}=0,1 \quad (26)$$

where Eqs. (3)–(9) correspond to the power, investment, emissions, job, operation and maintenance, distance and social acceptance goals; Eqs. (10)–(23) are the conservation of flow constraints for each node; Eq. (24) ensures that each place will be matched with one plant; Eq. (25) ensures that five plants must be located five locations; and Eq. (26) indicates that the flow variables are binary.

The problem was solved using Lingo and the solution is given in Tables 5 and 6. Table 5 shows the places where each plant should be located and Table 6 shows the deviations from the goals. Goals 1, 2, and 5 are achieved, while goals 3, 4, 6 and 7 are not achieved. The power generated is higher than the established goal, whereas the investment and operation and maintenance costs are lower than the established goals. The tons of emissions avoided, number of jobs created, maximum distance between plants, and social acceptance are lower than the established goals.

4. Conclusions

Mitigation of climate change requires the adequate policy formulation for fossil fuel energy substitution by renewable energy sources. In modern technologically developed societies, where the complexity of the interactions between the economic activities and and environmental systems are recognized, the capacity expansion planning problem of the renewable energy industry involve decisions regarding the optimal mix of different plant types, locations where each plant should be built, and capacity expansion decisions over the planning horizon for each plant.

In this paper a Goal Programming model, based on a multi-source multi-sink network, is applied to locate five renewable energy plants for electric generation in five places located in the autonomous region of Cantabria, in the north of Spain. As different types of plants can be placed in each location, the goal is to locate one plant in each place, maximizing the number of plants that are matched with comparable locations, in a way that the total deviations from goals are minimized. The model shows as Goal programming can be used as an efficient and effective tool to help decision-makers to attack problems in developing expansion plans for the renewable energy industry, where a multitude of conflicting goals exist.

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